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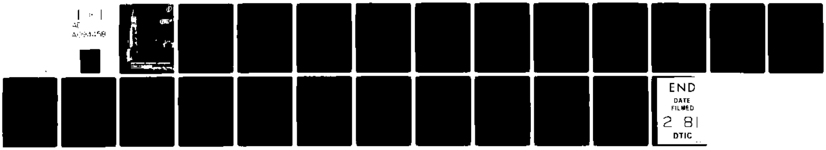

THIRD QUARTER PROGRESS REPORT. no. 3, 1 Jul-30 Sep 80

on

6 PLASMA THEORY AND SIMULATION.

July 1 - September 30, 1980

Research during the Third Quarter of 1980 is reported here.

Our research group uses both theory and simulation as tools in order to increase the understanding of instabilities, heating, transport and other phenomena in plasmas. We also work on the improvement of simulation, both theoretically and practically.

Our staff is: 10 12 23

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*Indicates ONR supported areas

Section I
PLASMA THEORY AND SIMULATION

A. LOWER-HYBRID DRIFT INSTABILITY

Yu-Jiuan Chen (Prof. C. K. Birdsall, Dr. B. I. Cohen, Dr. W. Nevins)

The study of the lower-hybrid drift instability saturation mechanisms in one-dimensional simulations was completed. An ERL report, Yu-Jiuan Chen and C. K. Birdsall, "Lower-Hybrid Drift Instability Saturation Mechanisms in One-Dimensional Simulations," ERL Memo No. UCB/ERL M80/40, September 19, 1980, was written, submitted to the Physics of Fluids and accompanies this report.

The nonlinear perturbation theory of the lower-hybrid drift instability was completed last quarter. An ERL report, Yu-Jiuan Chen and B. I. Cohen, "Nonlinear Frequency Shift Induced by the Lower-Hybrid Drift Instability," ERL Memo No. UCB/ERL M80/20, April 1, 1980 was sent out last quarter. With revisions, this has been accepted for publication in the Physics of Fluids.

Some progress has been made in studying the lower-hybrid drift instability using simulations in 2d with the EZOHAR code. In the last QPR, Fig. 1 showed a $v_E < 0$ near the left boundary ($x = 0$) due to an imperfection in the particle loader. It was found that instabilities grew rapidly in that region and heated up the electrons substantially in one ion transit time (the time needed for a thermal ion to cross the density scale length). We are improving our method of loading particles so that the initial density is as near our

theoretical equilibrium as possible.

B. MAGNETIZED MULTI-RING INSTABILITIES

Jin Soo Kim, Niels Otani (Prof. C. K. Birdsall)

The stability boundary for a Maxwellian made up of equally weighted, unevenly spaced rings was given in Fig. 5 in the previous QPR. A rough rule of thumb is that the number of rings, N, must obey

$$N > \frac{1}{3}\left(\frac{\omega_p}{\omega_c}\right)^2$$

for stability.

Some work is being done on equally spaced, unequally weighted rings.

The next step is to modify the dispersion relation so that it applies to rings made up of angular elements, in order to model the widely used "ring-and-spoke" particle loading. The stability requirement is expected to become more severe.

See Section II, Part F on JROOT, the solver used to obtain the stability criteria given in the previous QPR.

C. LINEAR STABILITY THEORY FOR LONG FIELD-REVERSING ION LAYERS, KINK MODES

Douglas Harned (Prof. C. K. Birdsall)

The stability of kink modes in long field-reversing ion layers immersed in a background plasma is investigated. There is assumed to be no variation in the axial direction (d/dz=0) and only frequencies which are low compared to the ion-cyclotron frequency are considered.

Growth rates and thresholds for instabilities are obtained by extending the theoretical development of Lovelace[1] through numerical techniques. The thresholds for instability are found to depend primarily on the self-magnetic field index and the Alfven speed of the background plasma.

D. QUASINEUTRAL SIMULATION OF KINK INSTABILITIES IN LONG FIELD-REVERSING ION LAYERS

Douglas Harned (Prof. C. K. Birdsall)

Kink instabilities in long field-reversing ion layers are investigated with the two-dimensional quasineutral simulation code, AQUARIUS. Ions are treated as particles and the electrons are treated as a massless fluid. The electron fluid equations and Maxwell's equations are coupled by the assumption of quasineutrality. Instability thresholds and growth rates were found to agree with theoretical predictions. Nonlinear effects have been observed to halt linear growth without destruction of the field-reversed state.

[1] R. V. Lovelace, "Precession and Kink Motion in Long Astron Layers," Physics of Fluids, 22, No. 4, pp. 708-717 (1979)

Section II
CODE DEVELOPMENT AND MAINTENANCE

A. ES1 CODE

No special progress.

B. EM1 CODE

No special progress.

C. EZOHAR CODE

See Lower Hybrid Drift Instability, Sec. 1, Part A.

D. RINGHYBRID CODE

Alex Friedman

The bulk of the progress this quarter has centered around the preparation of reports to be submitted for journal publication. The manuscript, "Strong Ion Ring Equilibria Formed by Injection and Intrinsic Stochasticity of Orbits," has been submitted to the Journal of Computational Physics; this material is essentially an updated version of ERL report No. M79/41. Another manuscript, "Stability of Field Reversed Ion Rings," is almost in a form suitable for an ERL report; it will be submitted to The Physics of Fluids. The work on "Simulation Studies of Exponential Rigid Rotor FRM and Ion Ring Equilibria" is in an earlier stage of preparation. An earlier paper, "Numerical Simulation of Injection and Resistive Trapping of Ion Rings," by A. Manofsky, A. Friedman, and R. N. Sudan, has been accepted for publication by Plasma Physics; this paper describes the RINGA magnetoinductive particle code and some applications.

E. POLARES: A TWO-DIMENSIONAL ELECTROSTATIC R-θ CODE

Niels Otani (Prof. C. K. Birdsall)

Following the unsatisfactory non-conservation of energy displayed by the code in the simulation of the plasma column dipole oscillation, the need for better diagnostics and therefore diagnostics organization has been realized and has precipitated a massive restructuring of the code. The new code will be in two parts: a slave program which contains all the particles, fields, and physics; and a master program, which contains the diagnostics and graphics. Simply put, the master will be in charge of stopping the slave program, taking snapshots and gathering history information while the slave is stopped, and then restarting the slave. This allows a great deal of diagnostics flexibility since the graphics is not entangled with the physics, reduces the memory penalty for using higher quality graphics packages such as DISSPLA, and additionally allows different priorities to be used with each of the two programs. The latter can be an advantage when the slave code is small, when small-to-moderate numbers of particles are used. It should also be possible to continue a run after termination and even run the program backwards if further diagnostics are required from the later stages of the run. Of some concern is the i/o time which will be required for master-slave communication. Preliminary tests indicate that the time required will be significant, but minimal.

F. JROOT: A SPECIAL PURPOSE ELECTROSTATIC DISPERSION RELATION SOLVER

Niels Otani (Prof. C. K. Birdsall)

Of interest in plasma simulation and certain heating applications is the behavior of velocity distributions in the form

$$f(v_\perp) = \sum_s a_s \delta(v_\perp - v_{\perp s})$$

where the a_s's are constants. In particular, electrostatic instabilities arising from distributions of this type in the presence of a uniform magnetic field are often visible and a nuisance in plasma simulations involving the plane perpendicular to the field.

This problem was originally investigated by Jin Soo Kim (see Sec. 1, Part B. Magnetized Multi-Ring Instabilities, this and prior QPR's) using the ROOTS electrostatic dispersion relation solver developed by Gerver[2]. For the case of a uniform plasma, the dispersion relation is

$$0 = \varepsilon(k,\omega) = 1 - \sum_s \frac{2}{kr_{gs}} \frac{\omega_{ps}^2}{\omega_c^2} \sum_{\ell=1}^{\infty} J_\ell(kr_{gs}) \cdot (J_{\ell-1}(kr_{gs}) - J_{\ell+1}(kr_{gs})) \frac{\ell^2}{\frac{\omega^2}{\omega_c^2} - \ell^2} \tag{1}$$

where ω_{ps} is the plasma frequency and r_{gs} is the gyroradius corresponding to the s-th velocity ring, and ω_c is the cyclotron frequency of the particles making up these rings (usually ions).

This dispersion relation is in principle solvable by the ROOTS program (modified to accomodate the large number of velocity rings generally involved); however, Kim found this to be an expensive and tedious process because of the difficulty encountered by the ROOTS program in following roots in complex ω-space, particularly in large-k regimes ($kv_{th}/\omega_c \gtrsim 10$) where instabilities typically occurred. (Here v_{th} is the thermal velocity.)

[2] M. J. Gerver, "ROOTS, A Dispersion Equation Solver," Memo No. ERL M77/27 Oct. 31, 1976.

The JROOT code was developed in response to these difficulties. Its scope is more limited than the ROOTS program, solving for only real roots, and only for the dispersion relation (1). However, it is considerably more efficient in finding roots for large k; dispersion diagrams for kv_{th}/ω_c as high as 120 and up may be generated with no difficulty using only modest amounts of computer time. Additionally, the small program size allows low priority execution.

JROOT may be described as a fairly standard Newton solver employing the dispersion relation (1) and its derivative with respect to ω^2 as the main tools for solution. No attempt is made to follow roots as k is incremented; instead, guesses are made for each value of k. These guesses are spaced two per each interval of $\frac{\omega}{\omega_c}$ in the following pattern:

$$\ldots, (n + \varepsilon)\frac{\omega}{\omega_c}, (n + 1 - \varepsilon)\frac{\omega}{\omega_c}, (n + 1 + \varepsilon)\frac{\omega}{\omega_c}, (n + 2 - \varepsilon)\frac{\omega}{\omega_c}, \ldots$$

where ε is a small parameter chosen by the user.

The reason for this pattern may be seen in Fig. 1. Here we see the three types of curves found in all dispersion functions so far examined. The curve on the left illustrates two pitfalls in iterating initial guesses to a solution. An attempt to use the guess on the right side of this curve often leads to an intermediate guess such as "a". The next guess will not be in the interval $\left[\frac{n\omega}{\omega_c}, \frac{(n+1)\omega}{\omega_c}\right]$ at all. We see, though, that the guess on the left side will converge to the root, because the concavity of the curve does not change between the initial guess and the root (typical).

Also notice that the root labeled 2 in the interval $\left[\frac{(n+1)\omega}{\omega_c}, \frac{(n+2)\omega}{\omega_c}\right]$ could not be found by any initial guess located in the

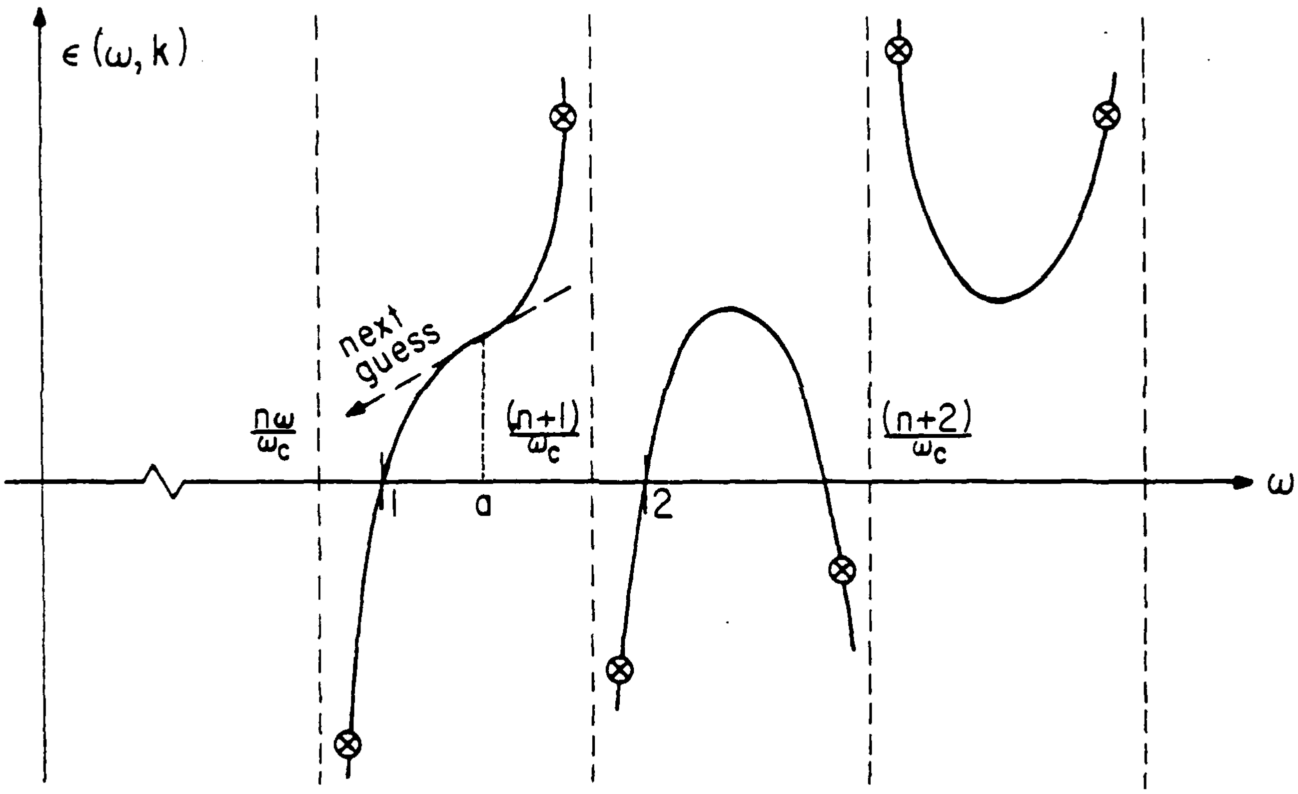


Fig. 1. Typical dispersion function for fixed k.
⊗ represents initial guesses.

interval $\left[\frac{n\omega}{\omega_c}, \frac{(n+1)\omega}{\omega_c}\right]$ except by luck. This explains the need for placing guesses in each interval. It may also explain why ROOTS has trouble following roots in some cases (i.e., those instances in which the real part of the roots crosses a multiple of ω/ω_c, with small or vanishing imaginary part).

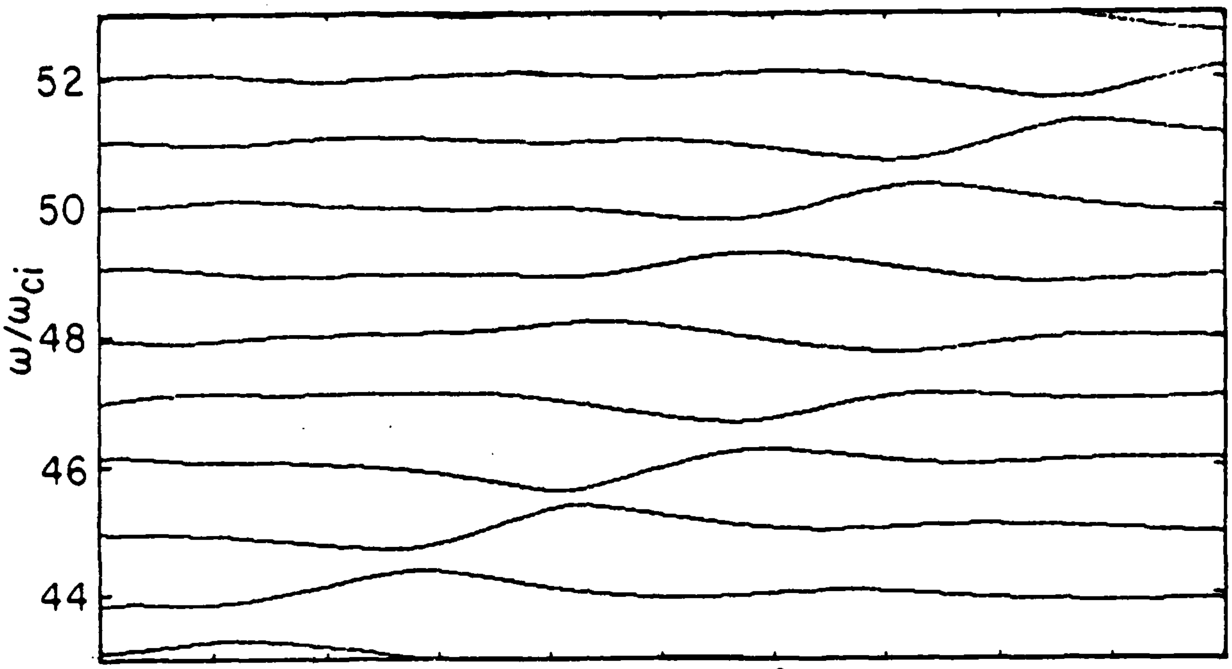
We conclude that the JROOT program has been very successful not only in plotting real roots versus k, but in determining thresholds for the onset of instability as well. The latter is characterized by the meeting and subsequent disappearance of two roots as k is varied; see Fig. 2. Typical unstable roots can be followed into the complex plane with equal ease, so that actual growth rates may be determined. Some optimism may be in order since we are essentially solving a polynomial equation with real coefficients. This means complex roots come in complex conjugate pairs; i.e., two degrees of freedom per two roots - the same ratio we have in the present real root solver.

G. KTEST: AN EXPERIMENTAL MODE-COUPLING SIMULATION CODE

Niels Otani (Prof. C. K. Birdsall, Dr. A. Drobot, NRL, SAI)

A brief test has been made of an idea due to Drobot concerning the study of mode-coupling using plasma simulation. The idea involves using the strategy employed in the azimuthal direction of the author's R-Θ POLARES simulation code in a one-dimensional periodic system. Specifically, we first compute the Fourier coefficients of the charge density ρ from (delta function) particles located at x_i, each with charge q_i

(a) shows JROOT's capability at large values of ω and k, for total $\frac{\omega_{pi}^2}{\omega_{ci}^2} = 220$ and 64 equal density velocity .



(b) shows the onset of instability when $\frac{\omega_{pi}^2}{\omega_{ci}^2}$ is increased to 240.

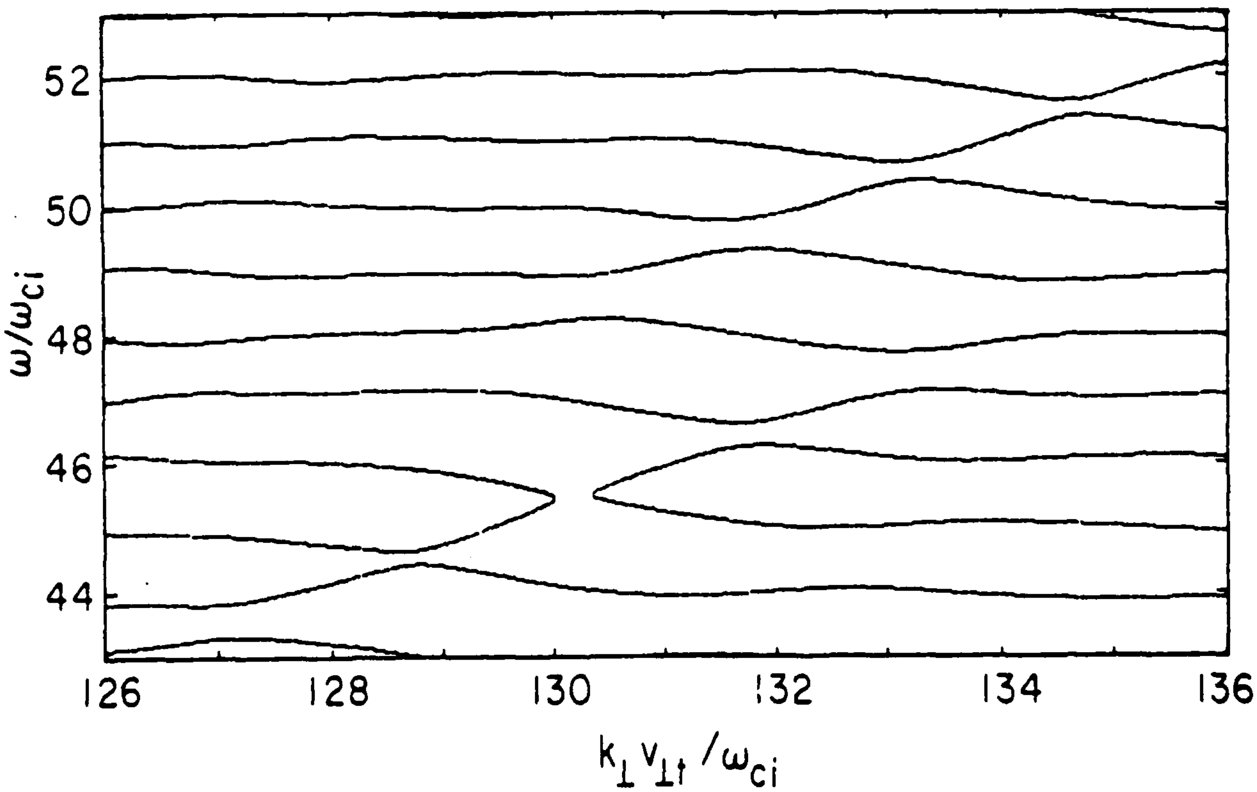


Fig. 2. Typical JROOT - generated dispersion diagrams.

$$\rho_k^{(c)} = \sum_{i=1}^{N} q_i \cos kx_i \qquad \rho_k^{(s)} = \sum_{i=1}^{N} q_i \sin kx_i$$

where i is the particle index, and c,s refer to the sine and cosine Fourier coefficients,

$$E_k^{(c)} = -\frac{4\pi\rho_k^{(s)}}{k} \qquad E_k^{(s)} = \frac{4\pi\rho_k^{(c)}}{k}$$

Finally the particles are pushed using the electric field

$$E(x_i) = \frac{2}{L}\sum_k (E_k^{(c)} \cos kx_i + E_k^{(s)} \sin kx_i)$$

where L is the length of the system $\equiv 2\pi$.

The mover is a standard time-centered, leapfrog mover. Notice there is no grid in x. The possible advantage of this scheme lies in keeping only those Fourier modes we wish to study. This eliminates the need for the fine grid normally required for simulations involving the coupling of modes with widely differing wavelengths.

In our simulation, we allowed a single-species cold plasma moving at velocity v_o to move across an external $k_o = 24$ mode static potential which was adiabatically turned on. The model is a beam interactive with a static sinusoidal potential, not unlike the ancient rippled-wall, rippled-beam amplifiers (see e.g., Birdsall[3]). The dispersion diagrams for the model are shown in Fig. 1. The mode ($k_1 = 476$) was excited initially (signal). v_o was chosen to couple the fast and slow space-charge waves ($v_o = 2\omega_p/k_o$), the pump ($\pm k_o$). The object was to look for the production of the idlers at $k_1 = k_o$, at frequencies ω_1, ω_2. The cleverness employed is keeping only two small windows in k space (modes 1 to 50 and modes 450 to 525).

Note that, since we must have $\Delta t \leq \frac{1}{k_1 v_o} = \frac{k_o}{2\omega_p k_1}$ which means

[3] C.K. Birdsall, "Rippled Wall and Rippled Stream Amplifiers," Proc. I.R.E., vol. 42, pp. 1628-1636. Nov. 1954.

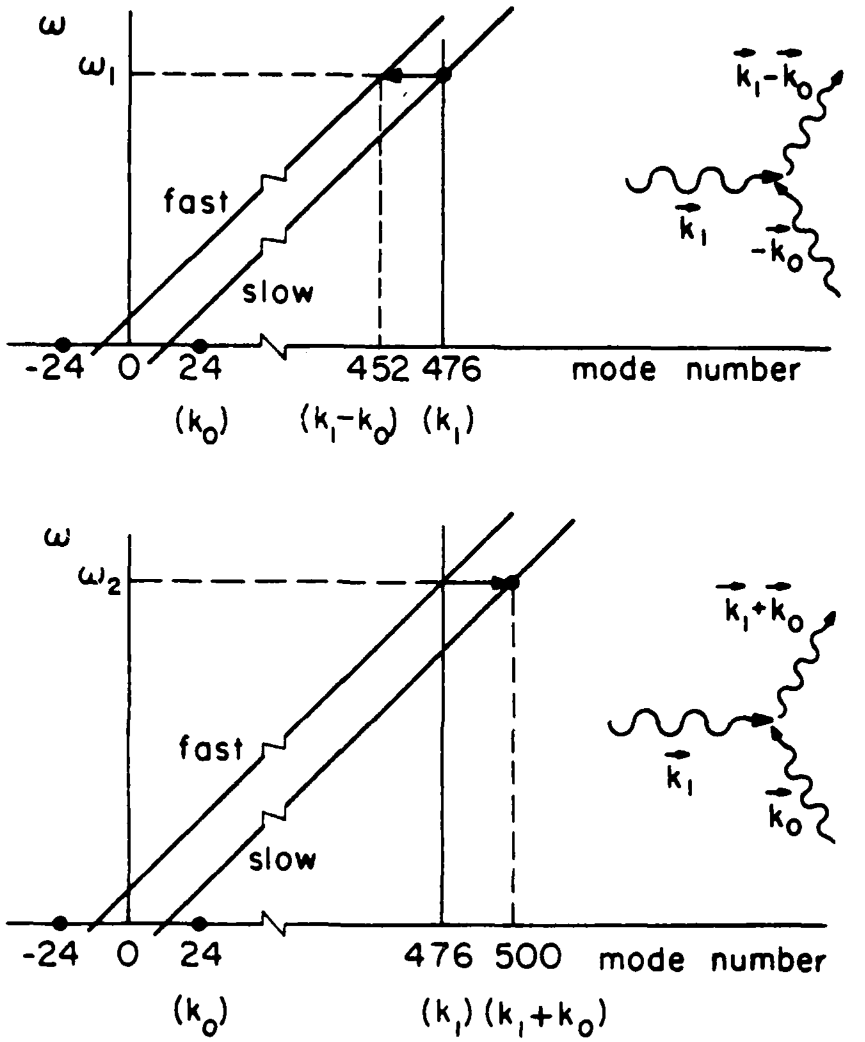


Fig. 1. Dispersion diagrams for dc pumped parametric beam device.

$\omega_p \Delta t \le \frac{k_o}{2k_1} << 1$ so that our runs require many timesteps and are consequently still somewhat time-consuming. Our trial runs used 25,600 timesteps (= 20 plasma periods) and 2048 particles.

Our results showed the growth and saturation of the main sidebands (modes 476±24) and also the growth of the secondary sideband 476 +2·24. Other modes also grew significantly. These were modes 452 + 4n for n = 1,2,3... These results are summarized in Fig. 2. No further analysis has been done to this point.

Thus our preliminary results show some promise for this method, but a more careful study is required for further discussion.

H. ORBIT AVERAGING AND IMPLICIT FIELD SOLVING USING THE FLUID EQUATIONS

Vincent Thomas (Prof. C. K. Birdsall, Dr. B. I. Cohen)

We are testing the use of orbit averaging (see previous QPR) in conjunction with the field implicit methods of Mason[1] and Denavit[2]. In their methods, the equation of continuity and the fluid force equation are used to obtain a prediction for an implicit electric field, which allows exceeding $\omega_p \Delta t \geq 2$ constraint for time centered movers. An important feature of this method is that the pressure term in the force equation is calculated directly from the particles. A restriction of the method is the requirement that the pressure term in the force

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[1] R.J. Mason, "Moment Equation Field Implicit Particle Simulation of Plasmas," LA-UR-80-2171, Aug. 1, 1980. Los Alamos Scientific Lab., Los Alamos, N.M.

[2] J. Denavit and J.M. Walsh, "Time Filtering Particle Simulations with $\omega_{pe}\Delta t >> 1$", Ninth Conf. on Numerical Simulation of Plasmas, Northwestern Univ., June 30-July 2, 1980.

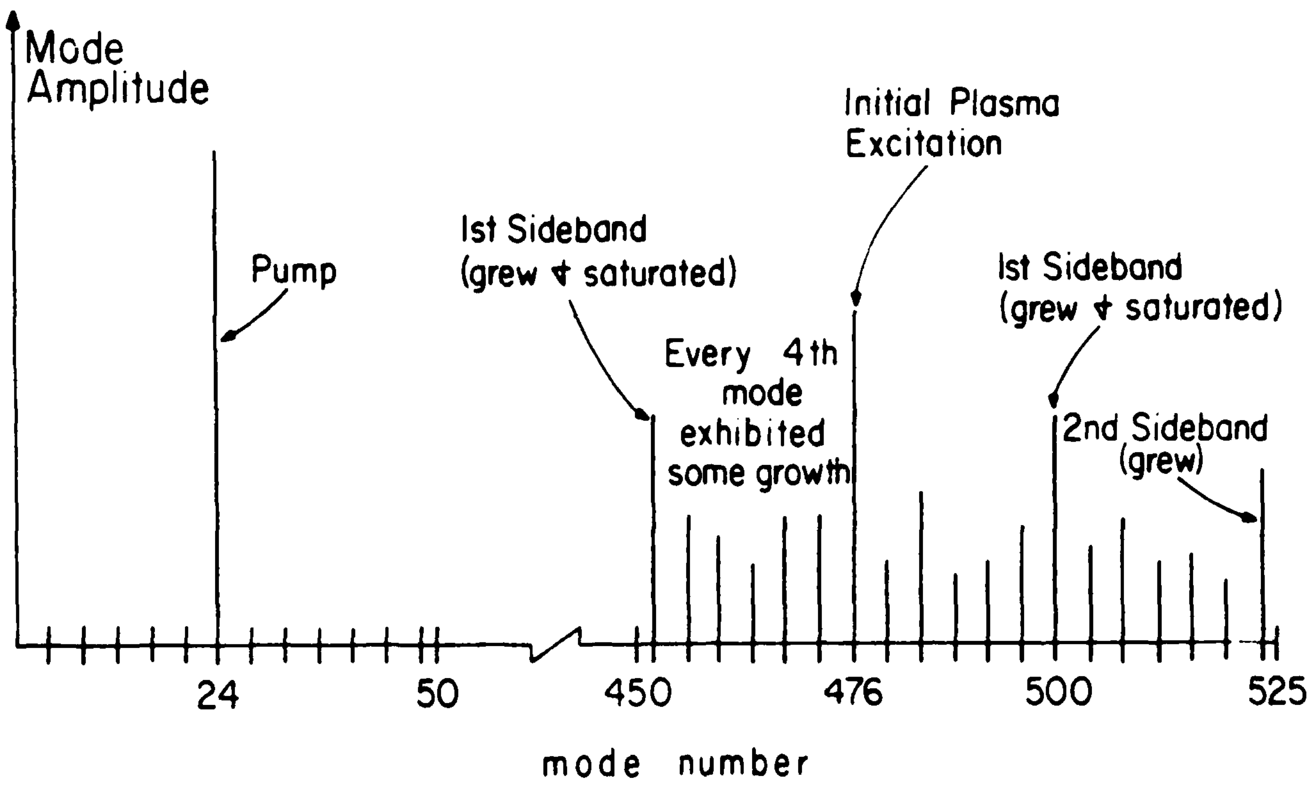

Fig. 2. Summary of KTEST results.

equation has to be small. This means that $kv_t\Delta t \ll 1$ for every wavelength kept in the system. Another constraint is that the electron plasma oscillations cannot be treated accurately for large time steps, and so they must be removed by artificial damping. This method is useful for studying low frequency laser pellet interactions and low frequency phenomena such as shocks and solitons.

I. IMPLICIT ALGORITHMS FOR PARTICLE SIMULATION

Alex Friedman (with A. Bruce Langdon and Bruce Cohen)

We have begun to explore the feasibility of a class of algorithms whereby the electric field in an electrostatic particle simulation is calculated at an advanced timestep, for purposes of overcoming the usual limit on the product of plasma frequency and timestep. Algorithms by Denavit and Mason accomplish this through the use of fluid equations for the low-order moments of the system.[1] We are considering a more direct approach, whereby the coupled particle-Poisson equations can be solved simultaneously at the advanced time level. Some of the advantages of an implicit time integration algorithm (should one prove feasible) have been noted by Langdon[2].

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[1] See Ref. 1 and 2 of preceding section.

[2] A. Bruce Langdon, "Analysis of the Time Integration in Plasma Simulation," J. Comp. Phys., 30, 202 (1979), esp. page 217.

SECTION III
SUMMARY OF REPORTS, TALKS, PUBLICATIONS, VISITORS

Papers and reports in preparation were mentioned in the body of the QPR.

Dr. Adam Drobot visited us for about two weeks in July and August, from Science Applications, Inc., McLean, Virginia, Plasma Physics Division and Naval Research Laboratory, Washington, D.C. He presented two special seminars:

"Computer Simulations with Finite Boundaries," on July 31;

and

"Continuity Equation Particle Codes," on August 7.

Dr. Dennis W. Hewett visited for about two weeks in August, from Los Alamos Scientific Laboratory, Los Alamos, N.M. He presented a special seminar on August 13,

"Computer Simulation of Formation and Reconnection in a Field Reversed Θ Pinch."

Dr. Toshi Tajima made a short visit and presented a special seminar on August 14,

"Properties of MHD - Particle Codes."

Three abstracts of papers prepared for the APS Division of Plasma Physics Meeting, November 10-14, 1980, at San Diego, follow:

(1) "Long-Layer Field-Reversed Plasma Simulation," D.S. Harned, A. Friedman, and C. K. Birdsall, U.C. Berkeley : Long-layer field-

reversed plasmas are studied using a two-dimensional quasineutral hybrid simulation code which is fully nonlinear. Ions are treated as particles and electrons are treated as an inertialess fluid. The Darwin version of Maxwell's equations and the electron fluid equations are coupled by the assumption of quasineutrality.

The quasineutral code has been applied to strong current ion layers immersed in a dense ($n_{layer}<n_{plasma}$) background plasma. Unstable m=2,3,4 and 5 modes have been observed, where m is the azimuthal mode number. Whether or not a mode exhibits exponential growth has been found to depend largely on the value of the self-magnetic field index. These linear stability results are in qualitative agreement with the theoretical predictions of Lovelace[1] for appropriate parameter ranges. The end of exponential growth of unstable modes has been observed. For simulations in which several modes are unstable, the saturation amplitudes have been found to be smallest for modes having the largest azimuthal mode numbers.

[1]R.V. Lovelace, Phys. Fluids 22, 708 (1979)

(2) "Lower-Hybrid Drift Instability Simulations in 2d," Yu-Jiuan Chen and C. K. Birdsall, U.C. Berkeley: The lower-hyrbrid drift instability, with electrons and ions treated fully nonlinearly, is studied in two-dimensional electrostatic particle simulations. The ions are unmagnetized (as $\omega_{real} >> \omega_{ci}$) and are initially in a steady equilibrium state. Simulation results agree well with the linear local theory, such as the linear growth rate and the mode frequency. Electron heating has

been observed during the growth of the instability. Both current relaxation (reduction of drift) and ion trapping appear to be involved in causing end of exponential growth or saturation of instability. Measurements of electron and ion diffusion will be presented and compared with results of quasilinear theory.

(3) "Structure of Unstable Modes of Field-Reversed Ion Rings; Stability of Exponential Rigid Rotor Equilibria," Alex Friedman, U.C. Berkeley: Detailed simulations of the unstable kink motion of a field-reversed ion ring in background plasma have been performed, using the linearized 3d hybrid code RINGHYBRID[1,2]. The tilting mode structure is that of a flipping motion rather than simple opposed axial displacements, but there is still no net change in $\underline{\mu}\cdot\underline{B}$ to first order. The magnitude of the mean displacement is roughly proportional to the distance from the ring center, so that the polar-angular displacement is nearly rigid.

The stability of exponential rigid rotor equilibria generated by the Vlasov equilibrium code RIGIDROTOR has been studied, using a "reconstruction" technique to overcome the effects of stochastic orbits[3,4]. In one case, the tilting mode has been stabilized by moving the endwalls in.

1 A. Friedman, J. Denavit, R.N. Sudan, Bul. APS 24, 956 (1979)

2 A. Friedman, R.N. Sudan, J. Denavit, Cornell Lab. of Plasma Studies Report #268 (1979), to appear in J. Comp. Phys.

3 A. Friedman, Proc. Sherwood Conf., 3B2 (Tucson, 1980)

4 A. Friedman, Proc. Ninth Conf. on Numerical Simulation of Plasmas, OB3 (Evanston, 1980)

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